A Programmable Architecture for OFDM-CDMA

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ABSTRACT Combining multicarrier (OFDM) and CDMA technologies is attractive for future wireless broadband communications and software radio realization. Based on the unified framework known as OFCDMA, we develop a programmable structure for OFDM-CDMA transceivers in spite of three different scenarios to combine OFDM and CDMA. By adjusting system parameters without changing the fundamental hardware and software architecture, various system scenarios can be implemented, which might serve as the foundation to design software radio.

In the diverse multisystem and multistandard wireless communication environment, software-defined radio is an extremely promising technology to compromise on needs from all aspects. Critical issues in designing software radio have been widely discussed in literature [1]. As wideband code-division multiple access (CDMA) has attracted the most attention in International Mobile Telecommunications in the year 2000 (IMT-2000) third-generation wireless systems primarily because of its higher capacity over conventional time-division multiple access (TDMA) and frequency-division multiple access (FDMA) techniques in cellular communication systems, soft realization of wideband CDMA radio invokes great interests in wireless communication research and advanced development. However, the performance of wideband CDMA suffers from multiple access interference (MAI) and inter-symbol interference (ISI) due to severe multipath fading. To better utilize the spectrum and radio resources for multimedia services with satisfactory bit error rate (BER), multi-carrier CDMA or orthogonal frequency-division multiplexing (OFDM)-CDMA is widely considered an effective means for future wireless multimedia communications.

Multicarrier transmission, also known as OFDM is used to combat frequency-selective multipath fading. In a multicarrier transmission system, the available channel bandwidth is divided into multiple subchannels such that data symbols modulated by different subcarriers can be transmitted in parallel. In order to make the most of the available bandwidth, spectra of adjacent subchannels are allowed to overlap without inter-channel interference (ICI) in such a manner that all information-bearing waveforms of the subchannels are orthogonal on some time interval. In an OFDM transmitter the original data stream with symbol duration T' is serial-to-parallel (S/P) converted to J groups of substreams with symbol duration T. The highest bandwidth efficiency is achieved by setting $T = JT'$. However, the usual approach is to design $T = JT' + T_g$, where T_g is the guard time. OFDM can mitigate frequency selective fading if T_g is greater than the delay spread of the channel, since the waveforms of the subchannels remain orthogonal on JT', which is then used for demodulation rather than T. OFDM systems are usually implemented using Fourier transform for two reasons: first, its programmability in digital implementation; and second, the existence of fast algorithms for Fourier transform. In digital implementation a cyclic prefix is used, with duration equivalent to the guard time T_g. The major disadvantage of OFDM is its high sensitivity to frequency offsets and waveform variations. Therefore, the data precision and linearity of the RF amplifier shall be taken into consideration [2].

Modern wireless multimedia communications adopting CDMA usually occupy a large bandwidth, resulting in possible frequency-selective fading for single-carrier transmission techniques. Multicarrier transmission, which adopts longer symbol duration (possibly with guard time to avoid frequency selectivity), has been proposed to aid CDMA in mitigating this problem while maintaining bandwidth efficiency by minimizing the separation between adjacent carriers. This greatly reduces the complexity of equalization or the RAKE receiver structure. On the other hand, OFDM combined with CDMA can result in finer partitioning of radio resources in the time, frequency, and code domains, so more effective radio resources allocation might be possible provided that an effective bandwidth allocation scheme is available [3]. All these suggest that OFDM-CDMA is an attractive candidate for future wireless communication; thus, its software radio realization is of significant interest.

OFDM-CDMA

Generally, three types of systems to combine OFDM and CDMA are presented in the literature:

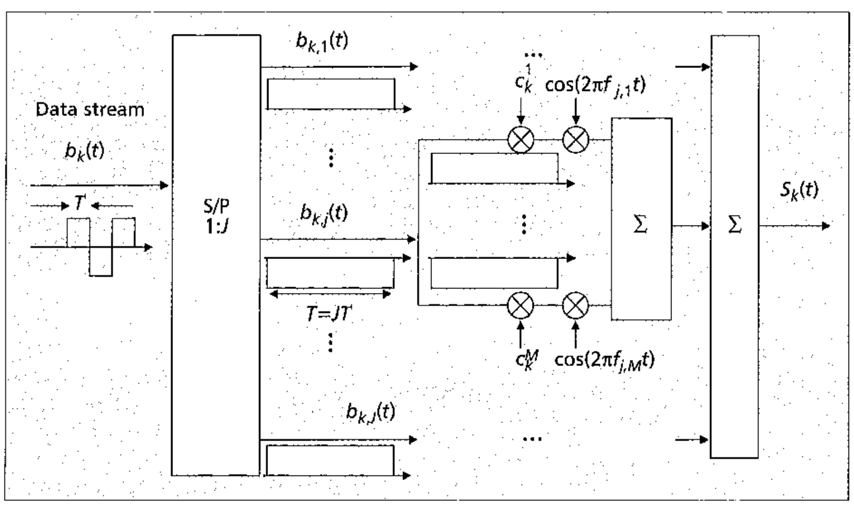

Figure 1a. *The transmitter of user* k *for MC-CDMA.*

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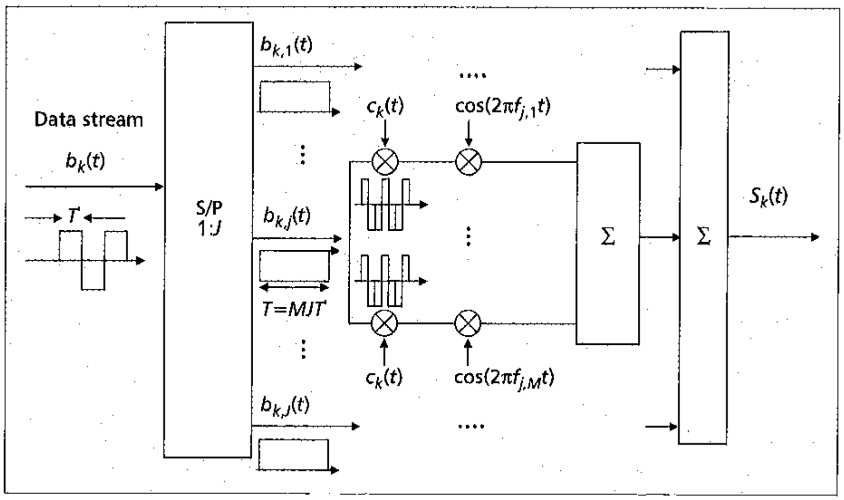


■ **Figure 1b.** *The transmitter of user k for MC-DS-CDMA.*

- Multicarrier-CDMA (MC-CDMA) [4, 5]
- Multicarrier direct sequence (DS)-CDMA (MC-DS-CDMA) [6]
- Multitone (MT)-CDMA [7]

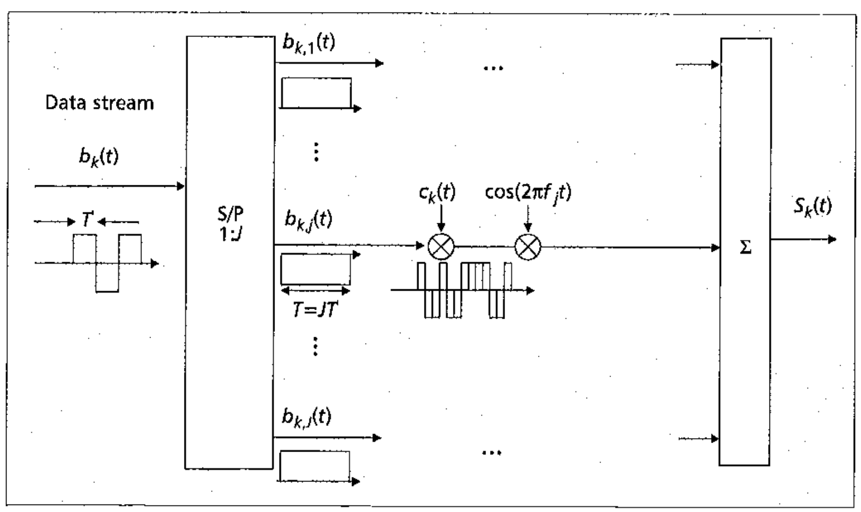
MC-CDMA — The MC-CDMA transmitter spreads the original data stream over different subcarriers using a given spreading code in the frequency domain [8]. Figure 1a shows the MC-CDMA transmitter of the kth user for a binary phase shift keying (BPSK) modulation scheme. The original data stream with symbol duration T' is S/P converted to J groups of data streams with symbol duration $T = JT'$. The sequence $(c_k^1 c_k^2 c_k^3 \dots c_k^M)$ constitutes a spreading code for user k. Then M identical branches of data streams for each group are spread by the spreading code. Finally, each branch modulates a subcarrier for transmission. The separation between adjacent carriers equals $1/T$ to satisfy the condition for orthogonality with minimum frequency separation.

MC-DS-CDMA — The MC-DS-CDMA transmitter spreads the S/P converted data streams using a given spreading code in the time domain so that the spectrum of each subcarrier is orthogonal with the minimum frequency separation [8]. Figure 1b shows the MC-DS-CDMA transmitter of the kth user for a BPSK scheme. The original data stream with symbol duration T' is S/P converted to J groups of data streams with symbol duration $T = MJT'$. Then M identical branches of the S/P converted data streams for each group are spread by the same signature waveform $c_k(t) = (c_k^1 c_k^2 c_k^3 \dots c_k^{N_{MD}})$, where N_{MD} denotes the processing gain. Finally, each branch modulates a subcarrier for transmission. The separation between adjacent carriers equals N_{MD}/T to satisfy the condition for orthogonality with minimum frequency separation.

MT-CDMA — The MT-CDMA transmitter spreads the S/P converted data streams using a given spreading code in the time domain so that the spectrum of each subcarrier prior to spreading is orthogonal with the minimum frequency separation [8]. Afterward, the spectrum of each subcarrier overlaps much more densely to possibly yield better spectral efficiency. Figure 1c shows the MT-CDMA transmitter of the kth user for a BPSK scheme. The original data stream with symbol duration T' is S/P converted to J groups of data streams with symbol duration $T = JT'$. The S/P converted data streams for all groups are spread by the same signature waveform $c_k(t) = (c_k^1 c_k^2 \dots c_k^{N_{MT}})$, where N_{MT} is the processing gain. And finally each group modulates a subcarrier for transmission. The separation between adjacent carriers equals $1/T$ to satisfy the condition for orthogonality with minimum frequency separation prior to spreading.

The purpose of the M identical information-bearing branches in MC-CDMA and MC-DS-CDMA is to increase frequency diversity. If the carrier separation between adjacent subchannels is big enough, they are subject to uncorrelated fading and provide frequency diversity. Therefore, M must be big enough to ensure the dimension of diversity but small enough to maintain uncorrelated fading. The design principle of the J multiplexed group after S/P conversion for the three schemes is to make each subchannel frequency nonselective. Therefore, J must be big enough to make each subchannel frequency nonselective under allowable complexity. Since multicarrier transmission spreads the total signal energy into several subchannels, under the conditions of no pilot tone and the same performance as single-carrier using complete subchannel information, the complexity of acquisition and synchronization for these type of systems grows (likely linearly depending on the detection scheme) with the number of subcarriers.

It is shown in [9] that MC-CDMA is preferable when all subcarriers are coherently modulated because spreading in the frequency domain needs reliable carrier and phase recovery. When noncoherent modulation is preferred in applications, MC-DS-CDMA and MT-CDMA have better performance. MT-CDMA has much denser spectrum overlap between subcarriers than MC-DS-CDMA for possibly better spectral efficiency. This property is advantageous to accommodate more users since a longer pseudo-noise (PN) sequence can be adopted when the available bandwidth is used. However, MT-



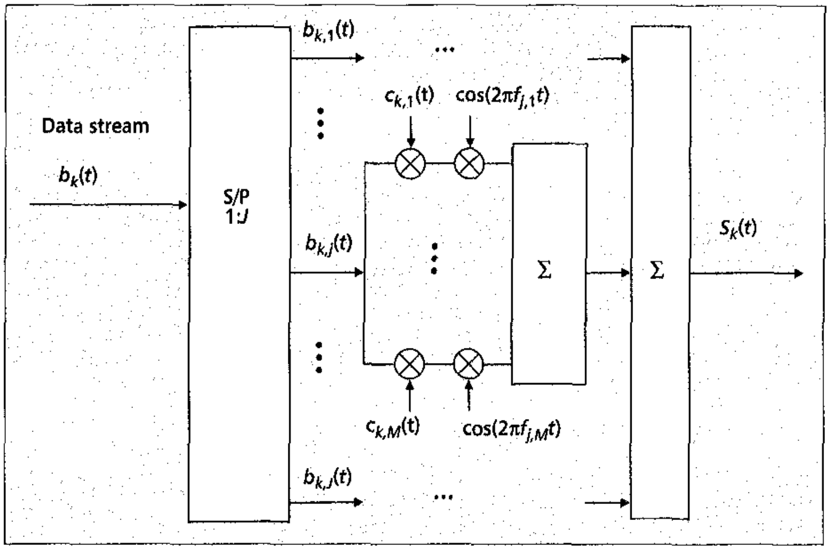
■ **Figure 1c.** *The transmitter of user k for MT-CDMA.*

CDMA more severely undergoes two types of interference, intercarrier interference and multicarrier MAI as discussed in [9]. Some techniques to improve BER, like equalization and joint multi-user detection, shall be considered in system design.

OFCDMA

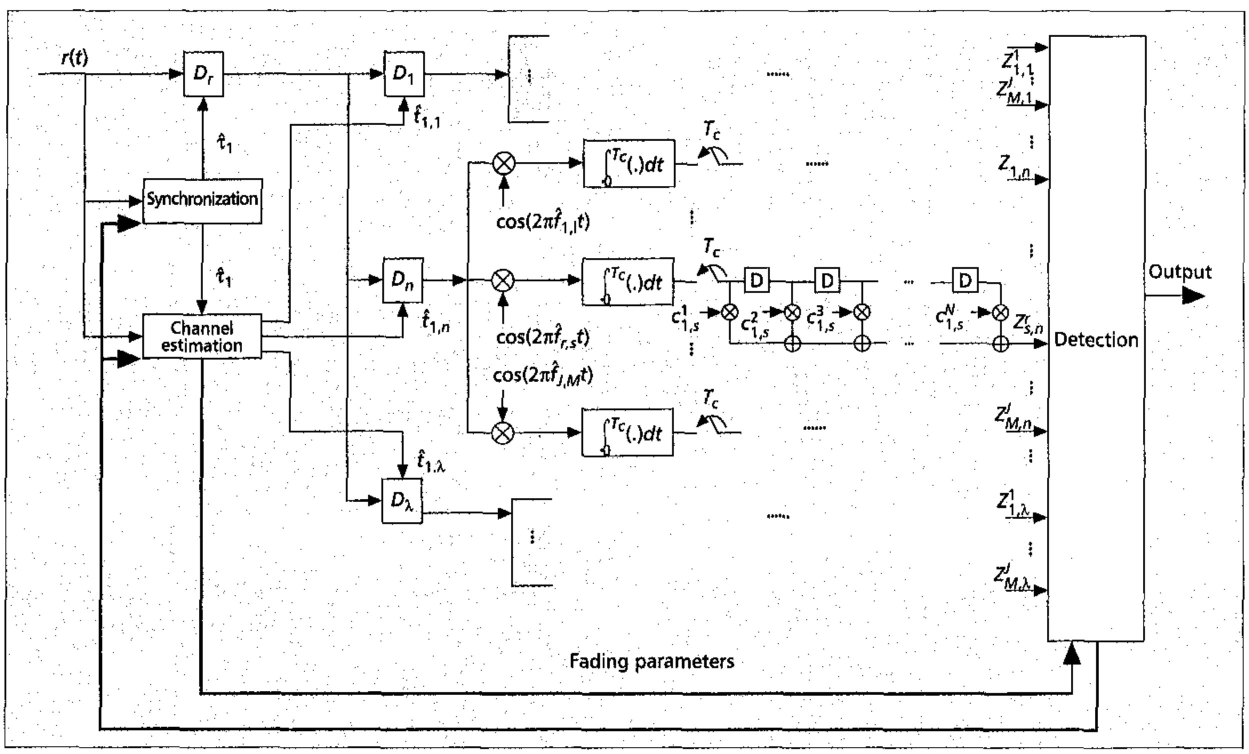
Three types of OFDM-CDMA systems can be described using a unified framework of OFCDMA developed in [9]. A programmable architecture based on OFCDMA can accommodate tradeoffs in practical applications of software radio. Figure 2a depicts its transmitter structure. The original data stream for user k is S/P converted to J groups of data streams, and M identical branches of data streams for each group are further spread by the signature waveform $c_{k,m}(t) = (c^1_{k,m} c^2_{k,m} \ldots c^N_{k,m})$. Finally, each branch modulates a subcarrier $\cos(2\pi f_{j,m}t)$ for $m = 1, 2, \ldots M$, $j = 1,2, \ldots J$. Let the minimum separation between carriers be $f_o = 1/T_o$, that is,

$$f_{a,b} - f_{c,d} = \frac{1}{T_o}(a-c) + \frac{J}{T_o}(b-d). \quad (1)$$



■ **Figure 2a.** *The transmitter of user k for OFCDMA.*

A RAKE receiver for OFCDMA is depicted in Fig. 2b. Without the loss of generality, the receiver for user 1 is described. The received signal $r(t)$ is synchronized by delay of $\hat{\tau}_1$ and is then locked to λ fingers of the RAKE receiver by delay of $\hat{\tau}_{1,n}$, for $n = 1, 2 \ldots \lambda$ respectively. Where $\hat{\tau}_1$ is the estimated path delay and $\hat{\tau}_{1,n}$, for $n = 1, 2, \ldots \lambda$ are the estimated delays for an L-ray multipath fading channel. In the nth finger, the synchronized signal is first demodulated for each of the MJ subcarriers, where $\hat{f}_{r,s}$ is the frequency estimator for each subcarrier. Then it is fed into an integrate-and-dump circuit with time interval T_c, the chip duration for the signature waveform, and sampled at the period of T_c. The sampled data are then passed to a tapped-delay-line with weighting coefficients $c^n_{1,s}$, for $n = 1, 2 \ldots N$ in order to despread the signal. We reset the tapped-delay-line filters at the period of $T = NT_c$. Finally, the outputs of the tapped-delay-



■ **Figure 2b.** *The RAKE receiver of user 1 for OFCDMA.*

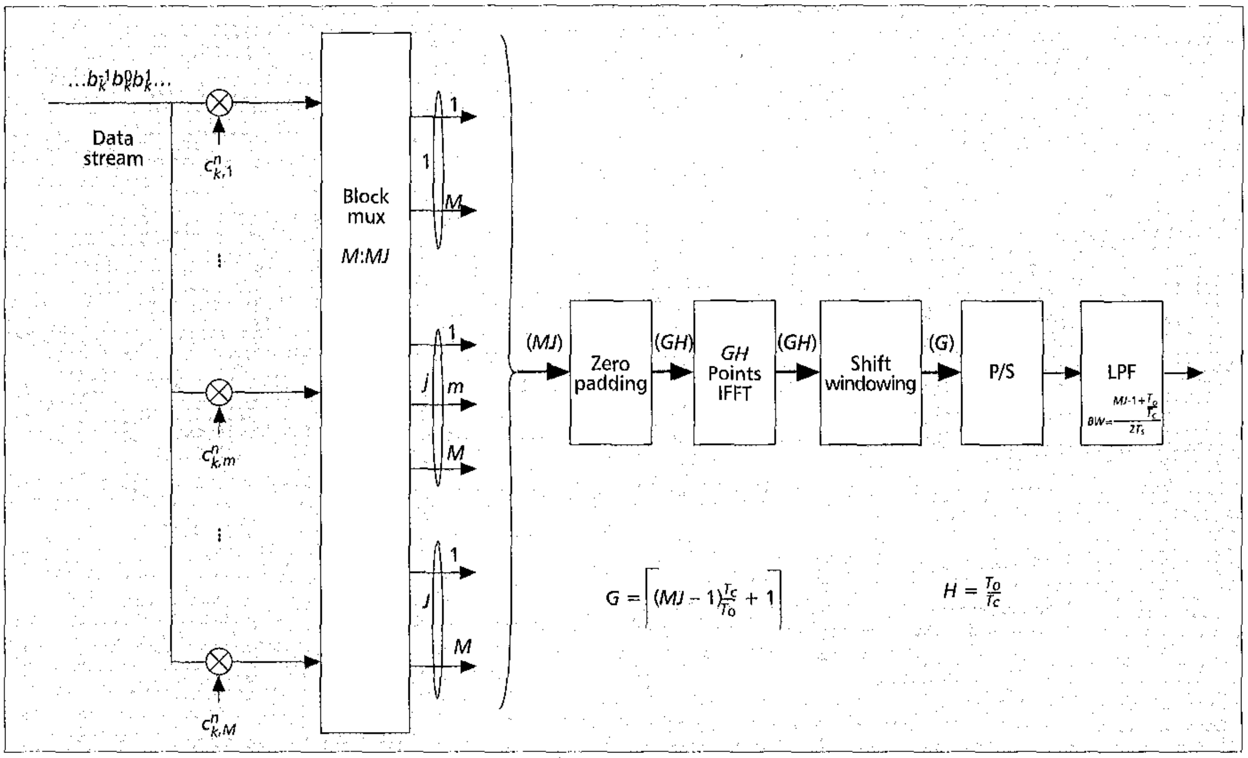


Figure 3a. *The digital transmitter of user* k *for OFCDMA.*

line filters of all subcarriers in all fingers, $z_{s,n}^r$ for $r = 1, \ldots J$, $s = 1, \ldots M$, $n = 1, \ldots \lambda$, are further processed to signal detection with the aid of estimated channel parameters. If the probability of detection is sufficiently high, those detected outputs are helpful for synchronization and channel estimation. Therefore, the detection outputs are fed back for synchronization and channel estimation in general. Of course, other techniques may be adopted, such as using a predefined sequence for synchronization or using a pilot tone for channel estimation.

The OFCDMA concept can describe all three types of systems: MC-CDMA, MC-DS-CDMA, and MT-CDMA. Transmitter structure of MC-CDMA depicted in Fig. 1a can be implemented using OFCDMA. The signature waveforms are designed such that $c_{k,m}(t) = c_k^m$, where $(c_k^1 c_k^2 \ldots c_k^M)$ constitute a PN sequence for user k, $T = JT'$, and $T_o = T$ (i.e., the minimum separation between carriers is $f_o = 1/T$).

The OFCDMA structure can be adapted into the MC-DS-CDMA transmitter depicted in Fig. 1b. The signature waveform is such that each subcarrier of user k has the same signature waveform, that is, $c_{k,m}(t) = c_k(t) = (c_k^1 c_k^2 \ldots c_k^{N_{MD}})$ and $T = MJT'$. Furthermore, if $T_o = T/N_{MD}$ (i.e., the minimum separation between carriers is $f_o = N_{MD}/T$), the transmitter of MC-DS-CDMA is a special case of Fig. 2a by setting the signature waveforms on all subcarriers the same (i.e., $c_{k,m}(t) = c_k(t)$), suggesting a simplification in real implementation.

Finally, OFCDMA can be transformed into MT-CDMA by taking only one branch in each group j, that is, $M = 1$, $c_{k,1}(t) \equiv c_k(t) = (c_k^1 c_k^2 \ldots c_k^{N_{MT}})$, and $T = JT'$. Setting $T_o = T$ (i.e., the minimum separation between carriers is $f_o = 1/T$), the transmitted signal is reduced to the transmitted signal for MT-CDMA. In Fig. 1c, there is only one branch for each group of the S/P converted data stream (i.e., setting $M = 1$) and, we define $c_{k,1}(t) \equiv c_k(t)$ for simplicity from Fig. 2a.

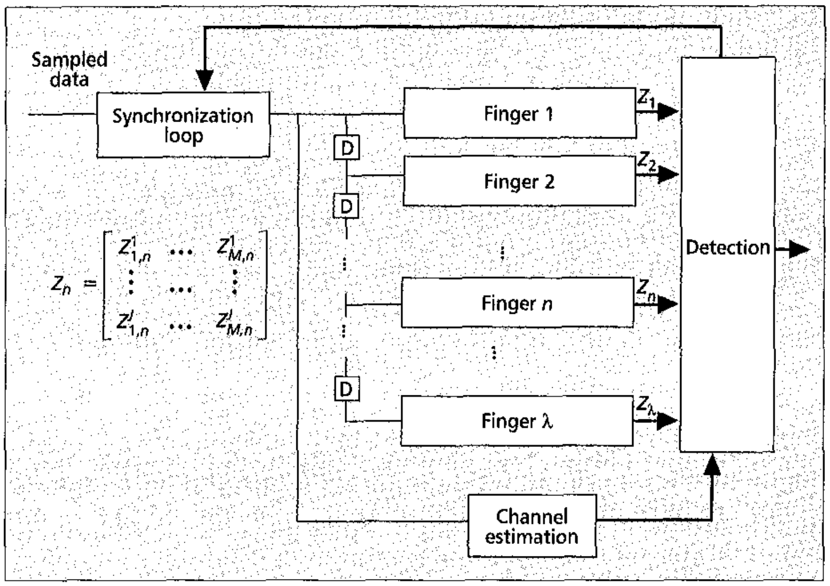
Programmable OFDM-CDMA Transceiver

In this section we demonstrate the capability of programmable OFDM-CDMA transceiver to accommodate different system structures as one of the major features of software-defined radio. Assuming that an appropriate RF section and analog–digital converter (ADC) available, the programmable transceiver operates at baseband to intermediate frequency (IF).

The transmitter of user k is shown in Fig. 3a. M identical branches of the original data stream with data rate $f_s = 1/T'$ are spread by the sequences $c_{k,m}^1 \ldots c_{k,m}^N$ for $m = 1, 2 \ldots M$. We define a block as a sequence of N spread samples at the output of the spreading operation. Then the M branches of the spread sequences are block-multiplexed (block muxed) to J groups; obviously, each group consists of M branches. The MJ samples produced by every operation of the MJ parallel branches are further zero-padded to GH samples in order to implement OFDM by inverse fast Fourier transform (IFFT), where $G = \lceil (MJ - 1)H + 1 \rceil$, $H = T_o/T_c$, and $\lceil x \rceil$ denotes the smallest integer greater than x. T_c is the duration of a chip time for the signature waveforms, and T_o is the inverse of the frequency separation between two neighboring subcarriers. After zero padding, the samples are processed by GH points IFFT. After IFFT operation, only some selected samples G are retained. This operation is the block denoted "Shift Windowing." Finally, the retained G-sample sequence is passed to an analog low-pass filter (LPF) with bandwidth

$$\frac{MJ - 1 + \frac{T_o}{T_c}}{2T_o}.$$

Figure 3b shows the programmable RAKE receiver architecture for the OFCDMA. The details of each finger in Fig.



■ **Figure 3b.** *The digital RAKE receiver of user 1 for OFCDMA.*

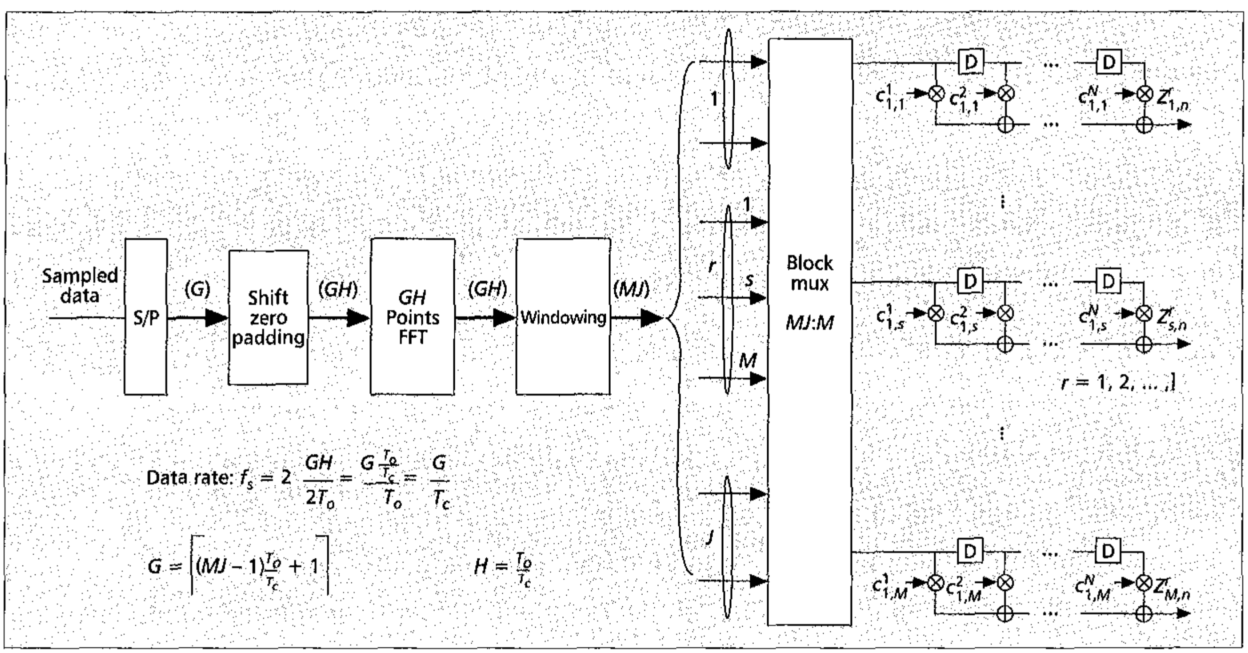
3b are shown in Fig. 3c. The data rate of the sampled data is $f_s = G/T_c$. In Fig. 3c, the G parallel branches are zero-padded and end-roundly shifted accordingly to GH parallel branches after S/P conversion from the sampled data with data rate $f_s = G/T_c$. Then the GH parallel samples are further processed by GH points FFT, and then only the first MJ samples of the transformed sequence are retained after windowing. Finally, N consecutive outputs of the MJ parallel branches are block-muxed to the input of M tapped-delay lines for despreading. The weightings for the sth tapped-delay line are $c^n_{1,s}$ for $n = 1, 2 \ldots N$. Finally, the outputs from those tapped-delay-line filters are the intended decision variables for detection.

The architecture described in Fig. 3 can be used to implement MC-CDMA, MC-DS-CDMA, and MT-CDMA, respectively. Parameter changes are discussed and summarized in Table 1, and the following subsections describe how OFCDMA is programmed to the three schemes.

OFCDMA Programmed to MC-CDMA — For MC-CDMA the signature sequences are programmed to $c^n_{k,m} = c^n_k$ for $m = 1, 2 \ldots M$. Because $H = T_o/T_c = T/T = 1$ and $G = MJ$, the zero padding and shift windowing blocks are not needed when $GH = MJ$ as shown before. The bandwidth of the LPF is $MJ/2T_o = MJ/2T_c = MJ/2JT' = M/2T'$, by recalling that $1/T'$ is the data rate of the original data stream. At the receiver end, the sampled data rate is $MJ/T_o = M/2T'$. The tapped-delay lines have only one tap (i.e., $N = 1$ for MC-CDMA) because of setting $c^n_{1,s} = c^s{}_1$, for $s = 1, 2, \ldots, M$.

OFCDMA Programmed to MC-DS-CDMA — For MC-DS-CDMA the signature sequences are programmed to $c^n_{k,m} = c^n_k$ for $n = 1, 2 \ldots N_{MD}$. Because $H = T_o/T_c = T_c/T_c = 1$ and $G = MJ$, the zero padding and shift windowing blocks are not used. The bandwidth of the LPF is $MJ/2T_c = MJN_{MD}/2MJT' = N_{MD}/2T'$. The RAKE receiver for MC-DS-CDMA operates with sampled data at $f_s = G/T_c = MJ/T_c = N_{MD}/T'$. Two blocks, shift zero padding and windowing, are not used because $GH = MJ$. As for the tapped-delay-line filters, all of those have identical sets of weighting coefficients (i.e., $c^n_{1,s}$ are set to $c^n_{1,s} = c^n_1$) for $n = 1, 2 \ldots N_{MD}$ and $s = 1, 2 \ldots M$. This suggests fast computation methodology in implementation.

OFCDMA Programmed to MT-CDMA — An MT-CDMA system has only one branch for spreading (i.e., $M = 1$), and



■ **Figure 3c.** *The nth finger of the digital RAKE receiver of user 1 for OFCDMA.*

we define $c_{k,1}^{n} = c_k^{n}$ for $n = 1, 2 \ldots N_{MT}$ for simplicity. Then the parameter for block mux is changed from $M{:}MJ$ to $1{:}J$. We see that $H = T_o/T_c = T/T_c = N_{MT}$ and $G = \lceil (MJ - 1)H + 1 \rceil = \lceil (J - 1)N_{MT} + 1 \rceil$. Unlike the other two schemes, the for zero padding and shift windowing blocks are needed since $GH \neq MJ$ in general. The bandwidth of the LPF is $(J - 1 + N_{MT})/2JT'$. The RAKE receiver for MT-CDMA operates with data sampled at $fs = G/T_c = GN_{MT}/T = GN_{MT}/JT'$. There is only one taped-delay-line filter by setting $M = 1$.

The changes addressed by programmability of the OFCDMA architecture are summarized in Table 1.

	MC-CDMA	MC-DS-CDMA	MT-CDMA
TX parameters	$G = MJ$	$G = MJ$	$G = \lceil (J-1)N_{MT} + 1 \rceil$
	$H = 1$	$H = 1$	$H = N_{MT}$
	$BW = \frac{M}{2T'}$	$BW = \frac{N_{MD}}{2T'}$	$BW = \frac{J-1+N_{MT}}{2JT'}$
RX parameters	$f_s = \frac{M}{T'}$	$f_s = \frac{N_{MD}}{T'}$	$f_s = \frac{GN_{MT}}{JT'}$
	$G = MJ$	$G = MJ$	$G = \lceil (J-1)N_{MT} + 1 \rceil$
	$H = 1$	$H = 1$	$H = N_{MT}$

■ **Table 1.** *OFCDMA parameter changes for MC-CDMA, MC-DS-CDMA, and MT-CDMA.*

IMPLEMENTATION ISSUES

The whole software architecture can be realized by the hardware structure shown in Fig. 4. Operating algorithms can be stored in ROM in advance. Based on the system selection, appropriate parameters and subroutines can be chosen and adjusted to perform the transceiver functions by proper controlling from the controller and properly executing digital signal processor (DSP) functions.

The low-pass filter (LPF) block in Fig. 3a consists of a digital–analog converter (DAC) and an analog LPF. It is a very important issue is whether one DAC can be applied to all multicarrier CDMA schemes. We see that the input data rates of the LPFs are different for the three schemes. To accommodate all three schemes, we can design a DAC with operating data rate greater than those in all schemes and adjust suitable bandwidth for the analog LPF of each scheme. Of course, the input data rate of the LPF for each scheme should be made equal by digital signal processing techniques such as interpolation, up sampling, and filtering. As for the ADC, we can select with the same sampling rate as the data rate of the DAC discussed earlier and down-sample the outputs following a digital LPF to meet the smaller data rate needed in each scheme. Therefore, it is possible to use one DAC/ADC to fit the three schemes at the price of a possible increase in computational complexity.

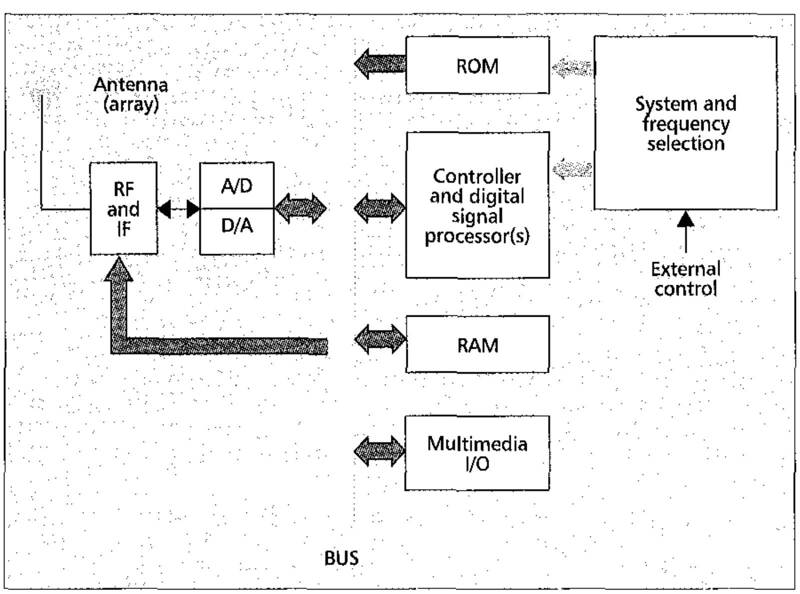
For the RF section, two important factors should be considered: the allocation of the signal band and the bandwidth of the RF transmitter. If the bandwidth of the RF transmitter is allowed to be sufficiently large, greater than that needed for all schemes, and the allocation of the signal band is fixed, only one RF function is needed. In general, the OFCDMA programmable structure fits multiband RF functions as long as there is enough bandwidth.

To improve system performance in practical systems, some well-known techniques may be included, such as pilot-aided signaling, forward error control (FEC), and equalization. Pilot-aided techniques can be very flexibly implemented in multi-carrier systems to enhance link performance. FEC can be applied either before, after, or between spreading and frequency-division multiplexing. Equalization can be realized as a filter (feed-forward and/or backward) into each subcarrier of our receiver without any difficulty. The best design choices really rely on system operation and can be incorporated into the proposed programmable structure. Some DSP techniques may also be useful for improving the performance. A modified cyclic prefix method (say generalized cyclic prefix) must be considered accordingly to alleviate interference caused by multipath fading.

It can be shown according to [10] that OFCDMA can be described in terms of synthesis/analysis configuration (transmultiplexer) of subband transforms. Some optimization approaches proposed in multirate signal processing may be useful for the OFCDMA scheme. For example, the spreading sequences for code division and the transformation (not necessary FFT) for orthogonal frequency division may be jointly designed and optimized under certain circumstances.

Finally, based on the programmable architecture proposed, we summarize the basic subroutines to perform OFDM-CDMA general transceiver functions:

- Modulation and demodulation
- Zero padding
- FFT
- Shift windowing
- Windowing filtering
- Multiplex
- Tap-delay-line filtering
- Synchronization, including frequency offset, timing, and likely phase recovery



■ **Figure 4.** *The general hardware structure to realize the proposed programmable transceiver.*

- Low-pass filtering
- Generalized cyclic prefix
- Up-sampling followed by filtering
- Down-sampling following filtering

CONCLUDING REMARKS

Through a general OFCDMA concept, we have demonstrated a programmable architecture such that multisystem OFDM-CDMA is possible based on one hardware and software platform. Despite remaining practical implementation issues, programmable architecture for multiple systems is valuable, providing the theoretical framework for software radio. Detailed design of the algorithms for different operating environments may simply follow a traditional approach with this programmable transceiver architecture.

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